Distributed Synchronization Algorithm for Infrastructure-less Public Safety Networks

Seonik Seong, Illsoo Sohn, Sunghyun Choi, and Kwang Bok Lee

Abstract: **In this paper, we propose a distributed synchronization algorithm for infrastructure-less public safety networks. The proposed algorithm aims to minimize the number of out-of-sync user equipments (UEs) by efficiently forming synchronization groups and selecting synchronization reference (SyncRef) UEs in a distributed manner. For the purpose, we introduce a novel affinity propagation technique which enables an autonomous decision at each UE based on local message-passing among neighboring UEs. Our simulation results show that the proposed algorithm reduces the number of out-of-sync UEs by up to 31% compared to the conventional scan-and-select strategy.**

Index Terms: **Affinity propagation, device-to-Device, infrastructure-less public safety networks, synchronization, synchronization groups and selecting synchronization reference (SyncRef) selection.**

I. INTRODUCTION

RECENTLY, public safety networks (PSNs) have been studied extensively as a special communication system for emergency situations. Given their world-wide commercial success, the 3rd Generation Partnership Project Long-Term Evolution (3GPP-LTE) systems have become very attractive as a unified platform for PSNs [1], [2]. LTE-based PSNs can provide high-speed data transmissions that enable various types of multimedia services. LTE-based PSNs inherit other benefits in terms of transmission reliability and power efficiency based on advanced wireless techniques such as hybrid ARQ and interference mitigation. Furthermore, using pre-existing eco-systems can significantly reduce implementation costs. Many pioneering countries including the United States [3], [4] and South Korea [5] have established plans to evolve toward LTE-based PSNs.

To cope with infrastructure-less environments such as the failure or destruction of network infrastructure, LTE-based PSNs enable direct communications between pairs of mobile devices to guarantee reliable communications in emergency situations [6], [7]. In 3GPP-LTE, device-to-device (D2D) communications have been first introduced in release-12. Device discovery and direct communications between devices are defined for various use cases, e.g., public safety, commercial applications, and internet-of-things (IoT) [8]. D2D relays, priority handling, and discovery in out-of-network coverage are supported for D2D enhancements in release-13. 3GPP release-14 further extends service scenarios including vehicle-to-vehicle (V2V) communications on the base of D2D communications. South Korea is likely to become the first country to commercialize LTE-based PSNs and has announced its official plan to deploy LTE-based PSNs by 2020.

Unlike typical cellular PSNs with infrastructure in which eNodeBs are responsible for synchronization by periodically broadcasting synchronization signals, infrastructure-less PSNs (IPSNs) face a challenge in that at least one user equipment (UE) should take over this responsibility. Thus, as a part of the current wireless standard activities, 3GPP task groups make great efforts to define UE-based synchronization procedures [9]. However, the issues of determining the synchronization reference (SyncRef) UEs that broadcast synchronization signals and the corresponding synchronization groups (SyncGroups) remain unsolved. Inappropriate choices of SyncRef UEs may lead to unnecessary power consumption of SyncRef UEs or to unacceptably low strength of the received signal at non-SyncRef UEs. In the worst case, non-SyncRef UEs that are located at the edge of a SyncGroup can experience a radio link failure (RLF), meaning the complete loss of the physical layer connection. Thus, SyncRef UEs and SyncGroups should be carefully determined considering the UE distribution.

The scan-and-select strategy is known to be a simple but efficient solution for the distributed synchronization of IPSNs, and hence, considered suitable for practical implementations [6]. The main idea is that a UE becomes a SyncRef UE if the UE cannot detect any synchronization signals or a UE becomes a member of the SyncGroup of the nearest SyncRef. Essentially, the scan-and-select strategy is a non-cooperative strategy because UEs do not share information or cooperate with others at the decision stage. This enables an autonomous decision at each UE based on independently collected local information. However, the scan-and-select strategy relies on greedy decisions, which make it clearly suboptimal.

In this paper, we propose a distributed algorithm that determines the SyncRef UEs and SyncGroups by introducing an affinity propagation (AP) framework [10]. AP is a novel clustering technique based on message-passing, and has been proven to be a very efficient tool for various types of optimization problems in communication networks [11]–[15]. By allowing local message-passing among neighboring UEs, the proposed algo-

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S. Seong is with Samsung Electronics Co., Gyeonggi-do, 16677, Korea, email: si.seong@samsung.com.

S. Choi, and K. B. Lee are with the Department of Electrical and Computer Engineering and the Institute of New Media and Communications, Seoul National University, Seoul 08826, Korea, email: {schoi, klee}@snu.ac.kr.

I. Sohn is with the Department of Computer Science and Engineering, Seoul National University of Science and Technology, Seoul 01811, Korea, email: isohn@seoultech.ac.kr.

K. B. Lee is the corresponding author.

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Table 1. Frequently used notations in Section II.

Notation	Definition
N	Number of UEs
$\mathcal{V}$	Set of SyncRef UEs
$\mathcal{N}_j$	Set of non-SyncRef UEs associated with SyncRef j
P	Transmit power of synchronization signals
d_{ij}	Distance between UE i and UE j
$s(i,j)$	Similarity of UE i to UE j

rithm efficiently solves the complicated optimization problem to determine SyncRef UEs, and enables an autonomous decision at each UE. This local cooperation based on message-passing allows the proposed algorithm to outperform the scan-and-select strategy significantly.

Our main contributions are summarized as follows:

- **SyncGroup organization:** We formulate the SyncRef selection problem in IPSN. Unlike the conventional synchronization algorithm which performs greedy selection, our formulation selects SyncRef UEs that minimize the expected number of out-of-sync UEs. The optimization problem belongs to a complex integer programming.
- **Distributed and collaborative algorithm:** We propose a distributed and collaborative synchronization algorithm in AP framework. The proposed algorithm iteratively exchanges and updates messages between pairs of neighboring UEs. In addition, we present overall distributed synchronization procedures showing how UEs initially participate in SyncRef selection procedures at the same timing without a central coordinator.
- **Reliable synchronization:** Our simulation results verify that the proposed algorithm reduces the average number of out-of-sync UEs in the network by up to 40% compared to the conventional synchronization algorithm. The robustness of the proposed algorithm in terms of mobility and quantization is also evaluated by simulation results.

The remainder of this paper is organized as follows. The system model and the problem formulation are described in Section II. In Section III, we propose a distributed synchronization algorithm based on message-passing. In Section IV, the procedures for distributed synchronization are proposed. We show the simulation results of the proposed algorithm in Section V. Finally, Section VI concludes this paper.

Notations: $\max(x,y)$ denotes the maximum of x and y. $\min(x,y)$ denotes the minimum of x and y. $\lceil x \rceil$ is used to refer to the smallest integer not less than x. $\mathbb{E}[\cdot]$ denotes the expected value of a random variable. $\mathbb{P}[\cdot]$ denotes the probability of an event occurring. A summary of the notations frequently used in this paper is listed in Table 1.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider an IPSN composed of N UEs. A subset of UEs become SyncRef UEs and periodically broadcast synchronization signals. The other UEs, referred to as non-SyncRef UEs, detect synchronization signals and select the strongest one as their synchronization reference. Fig. 1 illustrates synchronization of IPSNs, where the black UEs, white UEs, border lines,

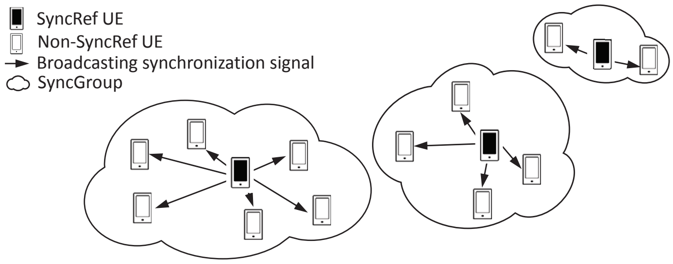

Fig. 1. Synchronization of infrastructure-less public safety networks.

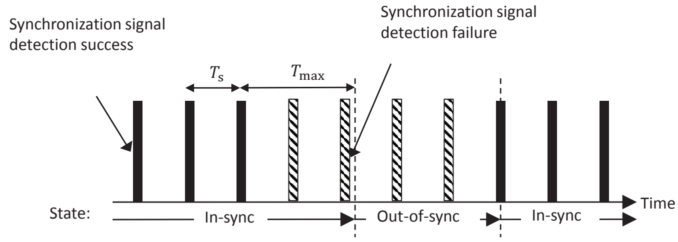

Fig. 2. Example of synchronization procedures.

and arrows denote the SyncRef UEs, non-SyncRef UEs, SyncGroups, and broadcasting synchronization signals, respectively. We assume a low-rate control channel to exchange information for SyncRef selection among neighboring UEs without prior synchronization. This can be implemented by embedding synchronization information in every transmitted data packet. One example of this type of channel is a physical sidelink broadcast channel (PSBCH) defined in 3GPP-LTE Rel-12 [16]. PSBCH does not have a mechanism to prevent a collision problem. Hence, collisions may occur in control channels, and messages in the control channels may not be received correctly. Note that the proposed algorithm is robust to partial loss of message. The impact of control channel collisions on the proposed algorithm is evaluated in Section V.

Assuming UE j as a candidate SyncRef UE of UE i, the received power of a synchronization signal at UE i is given by

$$P_{\mathrm{rx}}(i) = PX_{ij}L_0\left(\frac{d_{ij}}{d_0}\right)^{-\alpha}, \quad (1)$$

where P, X_{ij}, L_0, d_{ij}, d_0, and α denote the transmit power, the fading coefficient between UE i to UE j, the path-loss at the reference distance d_0, the distance between UE i and UE j, the reference distance, and path-loss exponent, respectively. We assume that the period of the synchronization signals, T_s, is greater than the coherence time of the channel. Then, X_{ij} is considered an independent random variable.

The detection of a synchronization signal is assumed to fail if the received signal-to-noise-ratio (SNR) of a synchronization signal is below a threshold γ, which is a minimum SNR required for the successful detection. The success of a synchronization signal detection is probabilistic due to channel fluctuations. The probability of a single failure of the synchronization signal detection at UE i, denoted by q_i, is

$$q_i = \mathbb{P}\left[\frac{P_{\text{rx}}(i)}{\sigma^2} < \gamma\right], \tag{2}$$

where σ^2 represents the noise power. For Rayleigh fading, where X_{ij} is exponentially distributed with unit mean, the failure probability is derived as [17]

$$q_i = 1 - \exp\left(-\frac{1}{2}\left(\frac{\gamma\sigma^2 d_{ij}^{\alpha}}{PL_0 d_0^{\alpha}}\right)^2\right). \tag{3}$$

Fig. 2 depicts an example of the synchronization procedures. A single detection failure of a synchronization signal does not immediately lead to an out-of-sync state. A UE falls into an out-of-sync state if detection failures continue for the maximum endurance time of T_{max}. The value of T_{max} is a system-defined parameter and is carefully determined considering the hardware requirements for the UE oscillators [6]. Thus, after $M = \lceil T_{\text{max}}/T_s \rceil$ consecutive failures of the synchronization signal detection, a UE falls into an out-of-sync state. The UE returns into an in-sync state after any single successful detection of the synchronization signal. The probability that UE i remains in an out-of-sync state is $p_i = q_i^M$.

We refer to UEs that are in an out-of-sync state and thus experience RLF as out-of-sync UEs hereafter. The number of out-of-sync UEs is the sum of the random variables Y_i's, where Y_i denotes the out-of-sync state of UE i. The random variable Y_i follows a Bernoulli distribution taking a value of '1' with probability p_i, and a value of '0' otherwise. The average number of out-of-sync UEs can be computed as follows:

$$\begin{aligned}\bar{N}_{\text{out}} &= \mathbb{E}\left[\sum_{i=1}^{N} 1 \cdot Y_i\right] \\ &= \sum_{i=1}^{N} \mathbb{E}[Y_i] \\ &= \sum_{i=1}^{N} p_i \\ &= \sum_{i=1}^{N}\left[1 - \exp\left(-\frac{1}{2}\left(\frac{\gamma\sigma^2 d_{ij}^{\alpha}}{PL_0 d_0^{\alpha}}\right)^2\right)\right]^M.\end{aligned} \tag{4}$$

Then, the selection of the SyncRef UEs that minimizes the number of out-of-sync UEs can be formulated as

$$\text{minimize} \sum_{j\in\mathcal{V}}\sum_{i\in\mathcal{N}_j}\left[1 - \exp\left(-\frac{1}{2}\left(\frac{\gamma\sigma^2 d_{ij}^{\alpha}}{PL_0 d_0^{\alpha}}\right)^2\right)\right]^M, \tag{5}$$

where $\mathcal{V}$ and $\mathcal{N}_j$ are the set of SyncRef UEs and the set of non-SyncRef UEs associated with SyncRef UE $j \in \mathcal{V}$, respectively. Note that the problem in (5) belongs to an integer programming typically requiring combinatorial optimization with exponentially growing computational complexity.

III. DISTRIBUTED SYNCHRONIZATION ALGORITHM BASED ON MESSAGE-PASSING

We develop a distributed algorithm that determines SyncRef UEs and SyncGroups by introducing an AP framework. AP is a novel clustering technique which is used to select a set of cluster heads among data points [10], [18]. The objective of AP is to select the set of cluster heads maximizing the sum similarities as formally described by

$$\text{maximize} \sum_{j\in\mathcal{V}}\sum_{i\in\mathcal{N}_j} s(i,j), \tag{6}$$

where the similarity $s(i,j)$ implies the suitability of UE j as the cluster head of UE i and the preference (or self-similarity) $s(j,j)$ of UE j implies the suitability of UE j to be a cluster head. The similarity $s(i,j)$ and the preference $s(j,j)$ are the real-valued similarities. All UEs are potential cluster heads in AP and cluster heads are determined by passing messages iteratively between the UEs.

Motivated by the analogy between our problem in (5) and AP in (6), we derive solutions by applying the AP framework to our problem. We define the similarity between UE i and UE j ($i \neq j$) as

$$s(i,j) = -\left[1 - \exp\left(-\frac{1}{2}\left(\frac{\gamma\sigma^2 d_{ij}^{\alpha}}{PL_0 d_0^{\alpha}}\right)^2\right)\right]^M. \tag{7}$$

With the above similarity definitions, maximizing the sum similarities in (6) becomes equivalent to minimizing the number of out-of-sync UEs in (5). The self-similarity (or preference) of each UE ($i = j$) is defined as

$$s(j,j) = \begin{cases} p, & \text{if UE } j \text{ is eligible as a SyncRef,} \\ -\infty, & \text{otherwise,} \end{cases} \tag{8}$$

where p is defined as a negative value. A pre-defined parameter p affects the number of UEs selected as SyncRef during SyncRef selection. We can exclude UEs with high mobility, or low residual energy from becoming SyncRef UEs by setting their preferences to $-\infty$.

According to AP [10], UEs iteratively exchange two types of messages, *responsibility* and *availability*, until finding a proper set of SyncRef UEs. Message update rules are derived based on the max-sum algorithm in a factor graph. The responsibility $r(i,j)$ from UE i to potential SyncRef UE j is updated as [10]

$$r(i,j) \leftarrow s(i,j) - \max_{j'\text{s.t.}j'\neq j}\left\{a(i,j') + s(i,j')\right\}. \tag{9}$$

The availability $a(i,j)$ from potential SyncRef UE j to UE i is updated as

$$a(i,j) \leftarrow \min\Big(0\,,\ r(j,j) + \sum_{i'\text{s.t.}i'\notin\{i,j\}} \max\left(0, r(i',j)\right)\Big). \tag{10}$$

Algorithm 1 Proposed Synchronization Algorithm

Initialization: $a(i,j) \leftarrow 0, r(i,j) \leftarrow s(i,j), t \leftarrow 1$
while $t \leq t_{\text{max}}$ & messages not converged **do**
    Each UE updates $r(i,j)$ using (9)
    Each UE updates $a(i,j)$ using (10) and (11)
    Send $a(i,j)$ & $r(i,j)$ to neighboring UEs
    $t \leftarrow t+1$
end while
Decision: Each UE determines its SyncRef using (12)

The self-availability of UE j is updated as

$$a(j,j) \leftarrow \sum_{i' \text{s.t.} i' \neq j} \max\{0, r(i',j)\}. \tag{11}$$

When there are messages which are not received correctly in the control channels, the messages updated in the latest iteration are used. Message exchanges terminate when the maximum number of iterations is reached or when messages remain unchanged for a fixed number of iterations.

The proposed algorithm is presented in Algorithm 1, where t denotes the iteration index and t_{max} denotes the maximum number of iterations. The algorithm starts by initializing messages as $a(i,j) = 0$ and $r(i,j) = s(i,j) - \max_{j' \text{s.t.} j' \neq j} s(i,j')$. Each UE continues to exchange "Responsibility" and "Availability" messages with neighboring UEs. During message exchanges, UE i updates availability $a(j,i)$ using (9) and updates responsibility $r(i,j)$ using (10) and (11) for neighboring UE j. At the beginning of each iteration, UEs check the termination condition. If the termination condition is satisfied, each UE autonomously determines whether to become a SyncRef or not. UE i computes its best SyncRef $j^\star$ as

$$j^\star = \arg\max_j [a(i,j) + r(i,j)]. \tag{12}$$

If $j^\star \neq i$, UE $j^\star$ becomes a SyncRef of UE i while UE i becomes a SyncRef itself if $j^\star = i$. The value of preference, p, is related to the number of SyncRef UEs. Eq. (12) shows that as the value of p increases, more UEs determine to become SyncRef UEs. The derivation of exact relation between the value of preference and the number of cluster heads in AP algorithm is a very difficult problem. Typically, the median or minimum of the other similarities is known as a good choice for the preferences [10]. In this work, we propose a preference determination strategy considering residual battery energy in Fig. 9.

The convergence property of the proposed synchronization algorithm is basically consistent with the convergence property of the AP algorithm. The convergence of AP algorithm is investigated in various studies [10], [13], [14]. The AP algorithm is probabilistically exact when the associated factor graph is a tree. When the associated factor graph is loopy as our optimization problem in (5), the AP algorithm is not guaranteed to converge within the configured number of iterations. However, even in the loopy case, the AP algorithm provides near-optimal performance with dozens of iterations as observed in most previous studies [13], [14].

The overall computational complexity of the proposed synchronization algorithm increases as $\mathcal{O}(K^2 t_{\text{max}})$, where K denotes the average number of neighboring UEs. In the proposed algorithm, each UE is responsible for updating its own messages. Thus, the computational burden on each UE is simply $\mathcal{O}(K t_{\text{max}})$, which is manageable considering that the number of neighboring UEs for a single UE is limited. Our simulation results in Section V show that the proposed synchronization algorithm outperforms the conventional scan-and-select algorithm with dozens of iterations.

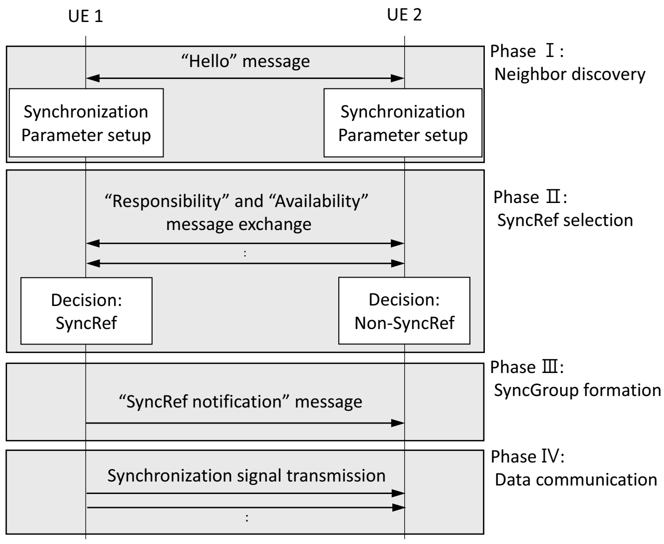

Fig. 3. Example of distributed synchronization with two UEs.

IV. DISTRIBUTED SYNCHRONIZATION PROCEDURES

The distributed synchronization procedures consist of four phases. Fig. 3 illustrates an example of distributed synchronization of two UEs. In Phase I, UEs discover their neighbors. Each UE broadcasts a "Hello" message containing its identity information and a reference signal to announce its existence. By decoding received "Hello" messages, UEs identify their neighbors. In addition, UEs estimate the distances to their neighbors by measuring the received power of the reference signal or by exchanging position information based on GPS in "Hello" messages. Each UE creates its neighbor list consisting of the identities of neighboring UEs and similarities between itself and them. In Phase II, UEs exchange messages with their neighbors according to the distributed synchronization algorithm described in Algorithm 1. Upon the termination of the algorithm, SyncRef UEs are selected. In Phase III, SyncGroups are formed. UEs selected to become SyncRef UEs announce their IDs through "SyncRef Notification" messages. Non-SyncRef UEs wait for "SyncRef Notification" messages from neighboring SyncRefs. When a "SyncRef Notification" message is detected, non-SyncRef UEs are synchronized to the SyncRef. If multiple "SyncRef Notification" messages are detected, the SyncRef with the strongest received power is selected. In Phase IV, typical data communication continues. SyncRef UEs in each SyncGroup periodically transmit synchronization signals for their members. Non-SyncRef UEs synchronize to the SyncRef

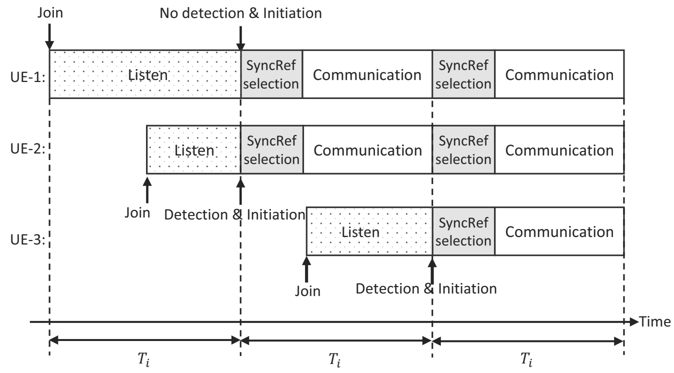

Fig. 4. Example of synchronization procedures with three UEs.

UE with the strongest received power. Overall synchronization procedure is repeated with a predetermined period.

When a UE first joins the network, it should wait until the start of the next round of synchronization procedure. A UE participates in the on-going synchronization procedure if a synchronization procedure is detected, i.e., by listening to "Hello" messages. If it fails to detect any synchronization procedure for more than a predetermined period, the UE initiates a synchronization procedure itself. Accordingly, UEs that join the IPSN are sequentially associated with synchronization procedures. Fig. 4 illustrates a detailed example of the UE's behavior related to the initiation and termination of the SyncRef selection, where T_i denotes a pre-configured period to repeat SyncRef selection procedures periodically. When the first UE, named UE-1, joins the PSN, no synchronization procedure is detected during an interval T_i. Thus, UE-1 initiates a synchronization procedure after T_i. If UE-2 joins the PSN, UE-2 detects the initiation of synchronization procedures from UE-1 within T_i. Then, UE-2 starts to exchange messages to select SyncRef UE as described in Fig. 4. UE-1 and UE-2 periodically repeat synchronization procedures at the same timing. Similarly, UE-3 can join the PSN, and get involved in the synchronization procedure successfully.

V. SIMULATION RESULTS

A. Simulation Set-up

The proposed algorithm is evaluated through extensive simulations. A square area of 5 km $\times$ 5 km is considered. We adopt the WINNER+ B1 path-loss model with $\alpha = 4.37$ and $L_0 = 0.068$ at a height of 1.5 m and a carrier frequency of 700 MHz [8], [28], which is the most preferred spectrum for public safety purpose globally. A transmit power of $P = 32$ dBm, and a noise power of $\sigma^2 = -104$ dBm are considered. We consider two SNR thresholds to detect a synchronization signal successfully: $\gamma = -6$ dB as an optimistic setting and $\gamma = 0$ dB as a conservative setting. UEs are considered to fall into an out-of-sync state after failing to detect a synchronization signal in the case of $M = 1$. To evaluate performance with the varying number of SyncRef UEs, the preference which decides the number of SyncRef UEs is controlled in $[-10, -0.1]$. The message-passing algorithm terminates when the number of iterations reaches $t_{\text{max}} = 100$ or when messages remain unchanged for 10 iterations. UEs are uniformly distributed in the square area and the performances are averaged over 100 independent realizations of user distributions. It is assumed that UEs are stationary in Figs. 5–12 except Fig. 10, where the impact of mobility is evaluated.

Table 2. Simulation parameters.

Parameter	Value
Area, S	5 km $\times$ 5 km
Number of UEs, N	1000, 750, 500
Pathloss exponent, α	4.37
Transmission loss at $d_0 = 1$ m, L_0	0.068 dB
Noise power, σ^2	-104 dBm
Transmit power for a synchronization signal, P	32 dBm
SNR threshold to detect a synchronization signal, γ	-6 dB, 0 dB

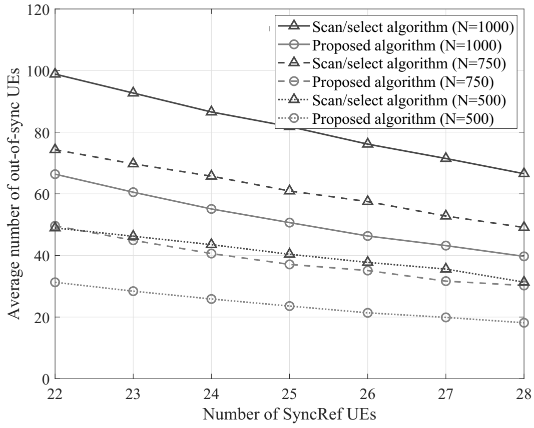

Fig. 5. Average number of out-of-sync UEs versus the number of SyncRefs for $\gamma = -6$ dB case.

B. Basic Simulation Results

Figs. 5 and 6 compares the average numbers of out-of-sync UEs in the proposed algorithm and in the scan-and-select strategy as a function of the number of SyncRefs when the number of UEs is $N = 1000$, 750, and 500 and the SNR threshold is $\gamma = -6$ dB and $\gamma = 0$ dB. As the number of SyncRef UEs (and SyncGroups) increases, the average number of out-of-sync UEs decreases because the average distance to SyncRef UEs decreases. We observe that the proposed algorithm outperforms the scan-and-select strategy in various environments. The proposed algorithm reduces the average number of out-of-sync UEs by up to 38.7% and 40.4% compared to the scan-and-select strategy when $\gamma = -6$ dB. In other words, to achieve the same out-of-sync performance, 27% more UEs should be selected as SyncRef UEs in the scan-and-select strategy. This indicates that the proposed algorithm can significantly reduce the unnecessary power consumption, signaling overhead, and potential interference in the network. The performance gain of the proposed algorithm stems from local information sharing between neighboring UEs for the collaborative optimization of SyncRef and SyncGroup determination.

Fig. 7 compares the empirical cumulative distribution function (CDF) of the number of asynchronous timings in the pro-

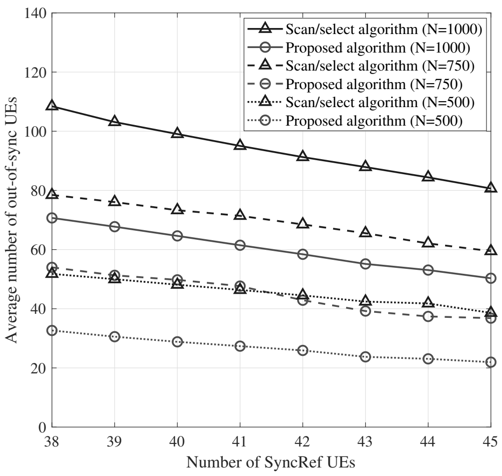

Fig. 6. Average number of out-of-sync UEs versus the number of SyncRefs for $\gamma = 0$ dB case.

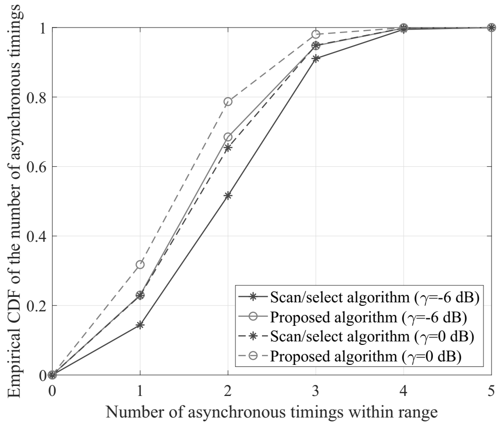

Fig. 7. CDF of the number of asynchronous timings when $N = 1000$.

posed algorithm and the scan-and-select strategy when $N = 1000$. The number of asynchronous timings is defined as the number of SyncRefs that a UE should keep tracking to successfully decode received signals from its neighboring UEs [22]. Typically, fewer asynchronous timings are preferred for UEs because tracking multiple asynchronous timings increases hardware complexity and power consumption of UEs. For a fair comparison, we consider cases with similar out-of-sync performance, i.e., 22 SyncRef UEs for the proposed algorithm and 28 SyncRef UEs for the scan-and-select strategy when $\gamma = -6$ dB, and 38 SyncRef UEs for the proposed algorithm and 45 SyncRef UEs for the scan-and-select strategy when $\gamma = 0$ dB, as shown in Figs. 5 and 6. Specifically, if we limit the number of asynchronous timings to two, 69% of UEs can communicate with all their neighbors in the proposed algorithm while only 51% of UEs can communicate with all their neighbors in the scan-and-select strategy.

C. Simulation Results for More Practical Modeling

The message exchange failure probability, denoted by p_e, is defined as the probability that a message is not received correctly on the control channels. Fig. 8 shows the average number of out-of-sync UEs versus the probability of message exchange failure in the control channels, when the number of UEs is $N = 1000$. Case 1 considers $\gamma = -6$ dB and 22 SyncRef UEs, Case 2 considers $\gamma = -6$ dB and 28 SyncRef UEs, Case 3 considers $\gamma = 0$ dB and 38 SyncRef UEs, and Case 4 considers $\gamma = 0$ dB and 45 SyncRef UEs. The results show the effect of failure of message exchanges on SyncRef selection in the proposed algorithm. As the message exchange failure probability increases, the average number of out-of-sync UEs also increases gradually. For $p_e \leq 0.5$, the proposed algorithm still notably outperforms the scan-and-select strategy in the same cases as shown in Figs. 5 and 6. The proposed algorithm gradually updates messages based on message-passing and still converges regardless of partial loss of messages in control channels. If the message loss surpasses the system endurance level, e.g., $p_e > 0.5$ in Fig. 8, the proposed algorithm fails to converge, leading to significant performance degradation. However, this is considered an extreme case. The simulation results imply that the proposed algorithm can be implemented with the control channel of the PSBCH defined in 3GPP-LTE in the presence of potential collision probability.

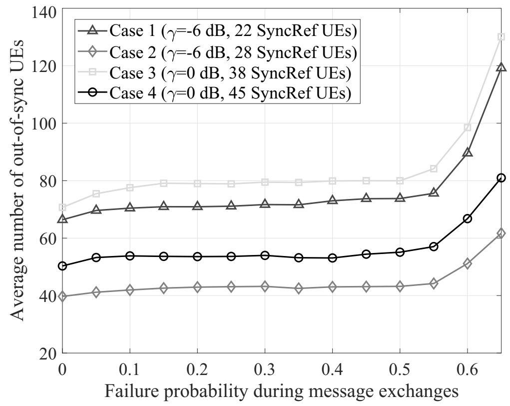

Fig. 8. Average number of out-of-sync UEs versus the message exchange failure probability.

Table 3 shows how the average number of out-of-sync UEs varies with the number of iterations in the proposed algorithm. Case A considers $N = 1000$, $\gamma = -6$ dB, and 22 SyncRef UEs, Case B considers $N = 1000$, $\gamma = 0$ dB, and 38 SyncRef UEs, and Case C considers $N = 500$, $\gamma = -6$ dB, and 22 SyncRef UEs. In general, larger number of iterations improves the performance of the proposed algorithm. However, the algorithm complexity can be considerably reduced by slightly sacrificing the performance. Note that the proposed algorithm with $t_{\max} = 20$ still notably outperforms the scan-and-select strategy. Extensive simulation studies have shown that a small number of iterations typically suffices convergence in the AP framework [13]. More details on the convergence properties and proofs can be found in [14] and references therein. Considering that periodic renewals of SyncRefs are performed on a long-term time scale, signaling overhead and computational cost required for the proposed algorithm are manageable.

Fig. 9 shows the empirical CDF of the residual battery energy

Table 3. Average number of out-of-sync UEs vs number of iterations.

	Proposed algorithm					Scan/select algorithm
# of iterations	20	40	60	80	100	
Case A	69.4	68.0	67.1	66.9	66.4	98.9
Case B	72.1	71.2	71.2	70.7	70.1	108.4
Case C	31.5	31.2	31.2	31.1	31.0	49.0

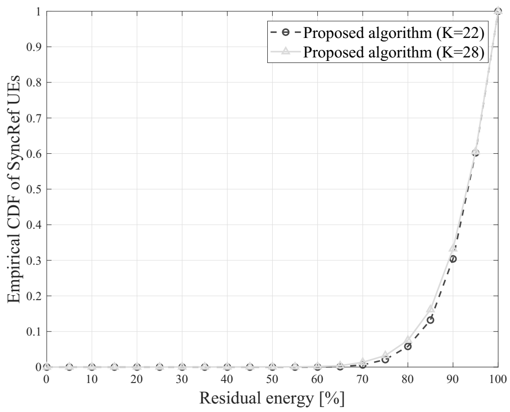

Fig. 9. Empirical CDF of the number of SyncRef UEs where $\gamma = -6$ dB, and $N = 500$.

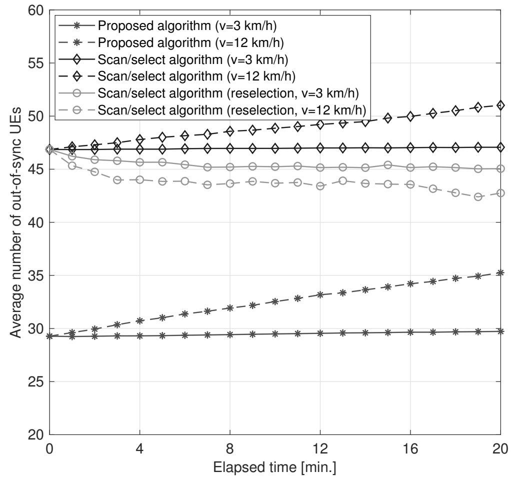

Fig. 10. Average number of out-of-sync UEs versus elapsed time where $\gamma = -6$ dB, 23 SyncRef UEs, and $N = 500$.

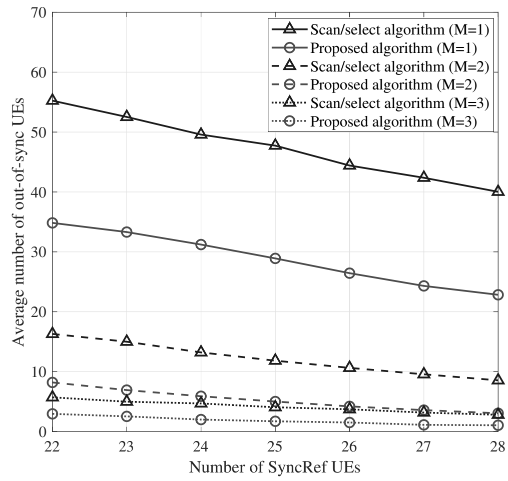

Fig. 11. Average number of out-of-sync UEs versus the number of SyncRefs where $M = 1$, 2, and 3, and $N = 500$.

levels of SyncRef UEs when the residual battery energy levels of UEs are i.i.d random variables uniformly distributed between 0% and 100% where $\gamma = -6$ dB, and $N = 500$. We set the preference of UE j as $s(j, j) = p_0/E_j$, where p_0 denotes the preference of UEs with a fully-charged battery, and E_j denotes the fractional residual energy of UE j's battery. The value of p_0 is a system parameter which should be less than zero and is determined by the density of SyncRef UEs in IPSN. We set the value of the preference of the UEs with a fully-charged battery as $p_0 = -4$ in Fig. 9. By this setting, UEs with a higher battery energy level set their preferences to higher values and are more likely to be SyncRef UEs as shown in Fig. 9. UEs with less than 70% battery energy are rarely selected as SyncRef UE in the proposed algorithm. SyncRef UEs consume additional energy to transmit synchronization signals and the preference setting helps UEs with low residual energy prolong their battery lifetimes.

Fig. 10 shows the average number of out-of-sync UEs in the proposed clustering algorithm as a function of elapsed time and UE speed, denoted by v, where $\gamma = -6$ dB, 23 SyncRefUEs, and $N = 500$. A random walk model [30], one of the most widely employed mobility models in ad-hoc network [31] and sensor network [32], is used for UEs' mobility patterns. After the proposed algorithm selects SyncRef UEs that minimize the average number of out-of-sync UEs, the average number of out-of-sync UEs increases due to mobility. As UEs move faster, the number of out-of-sync UEs increases rapidly, and therefore SyncRef selection procedures should be performed more frequently to maintain reliable synchronizations. However, with iteration of the SyncRef selection procedures every 10 minutes, the increase in the average number of out-of-sync UEs remains below 15% when the UEs move at a speed of $v = 12$ km/h. Even in the case that all UEs are stationary, the SyncRef selection procedures should be periodically performed to reflect changes in the IPSN caused by UEs' join and leave. Thus, the pre-configured period for repeating SyncRef selection procedures can be set as $T_{\mathrm{p}} = \min(t_{\mathrm{p}}(x), T_{\mathrm{p,min}})$, where $t_{\mathrm{p}}(x)$ denotes the maximum time interval where the increase in the average number of out-of-sync UEs is less than x percent, and $T_{\mathrm{p,min}}$ is the minimum period interval for repeating SyncRef selection procedures.

Fig. 11 shows the average number of out-of-sync UEs as the number of SyncRef UEs increases for three different values of M, which denotes the number of consecutive synchronization failures resulting in an out-of-sync state. Because M is an exponent in (5), the average number of out-of-sync UEs for a larger M is much less than the average number of of out-of-sync UEs for smaller M in both of the proposed algorithm and the scan-and-select algorithm. An increase of M by one results in a reduction of the average number of out-of-sync UEs by up to 77%. For all values of M, the proposed algorithm shows smaller number of out-of-sync UEs than the scan-and-select algorithm.

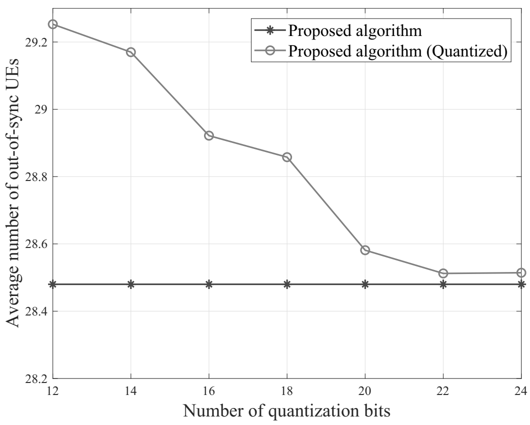

Fig. 12. Average number of out-of-sync UEs versus the number of quantization bits of messages where $\gamma = -6$ dB, 23 SyncRef UEs, and $N = 500$.

Fig. 12 shows how the average number of out-of-sync UEs varies according to the number of quantization bits of messages, N_q, where $\gamma = -6$ dB, 23 SyncRef UEs, and $N = 500$. Availability messages and responsibility messages should be quantized before being transmitted to neighboring UEs in practical implementation. In order to provide simulation results in more practical scenarios, the impact of the number of quantization bits is shown in Fig. 12. When the number of quantization bit is too small, the effect of message quantization becomes the bottleneck of the convergence of the proposed algorithm. For the convergence of the proposed algorithm, the number of quantization bits per message should be greater than or equal to 12 bits. The number of out-of-sync UEs decreases with larger number of quantization bits in Fig. 12 although the performance difference is very little. In quantization of responsibility and availability, two bytes seem to be sufficient for each message.

VI. CONCLUSION

In this study, we develop a distributed synchronization algorithm in the affinity propagation framework. By allowing local message-passing, the proposed algorithm enables autonomous decisions to determine SyncRefs and SyncGroups. Simulation results shows that the proposed algorithm considerably outperforms the existing scan-and-select strategy. Our future research direction includes an extension of the proposed algorithm to multi-hop synchronization model.

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Seonik Seong received his B.S. degree in Electrical Engineering from Pohang University of Science and Technology (POSTECH) in 2008 and received Ph.D. at the Department of Electrical and Computer Engineering, Seoul National University (SNU) in 2016. Currently, he is working with Samsung Electronics, Co. Ltd., Mobile Division as software engineer. His research interests include wireless networks and mobile communications system.

Illsoo Sohn received the B.S., M.S., and Ph.D. degrees in 2003, 2005, and 2009, respectively from Seoul National University, Seoul, Korea, all in the field of Electrical Engineering. He worked as a postdoctoral researcher at Wireless Networking and Communication Group, University of Texas at Austin from 2009 to 2010. He worked as a Senior Research Engineer at Advanced Communication Technology Research Lab., LG Electronics, Anyang, Korea from 2010 to 2012. He worked as a Network Design Engineer at Network Strategy Department, Korea Telecom (KT), Seongnam, Korea from 2012 to 2013. From 2013 to 2017, he worked as an assistant professor at the Department of Electronic Engineering in Gachon University. From 2017, he is an Assistant Professor at the Department of Computer Science and Engineering in Seoul National University of Science and Technologies (SeoulTech). His current research interests include statistical inference, message-passing algorithms, multi-user MIMO, multi-cell MIMO, time division duplex, distributed antennas systems, and cross-layer optimization.

Sunghyun Choi is a professor at the Department of Electrical and Computer Engineering, Seoul National University (SNU), Seoul, Korea. Before joining SNU in September 2002, he was with Philips Research USA, Briarcliff Manor, New York, USA, as a Senior Member Research Staff for three years. He was also a visiting associate professor at the Electrical Engineering department, Stanford University, USA, from June 2009 to June 2010. He received his B.S. (summa cum laude) and M.S. degrees in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST) in 1992 and 1994, respectively, and received Ph.D. at the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor in September, 1999.

His current research interests are in the area of wireless/mobile networks with emphasis on IoT connectivity, WLAN/WPAN, next-generation mobile networks, and acoustic communication. He co-authored over 220 technical papers and a book "Broadband Wireless Access and Local Networks: Mobile WiMAX and WiFi," Artech House, 2008 (with B. G. Lee). He holds over 140 patents, and numerous patents pending. He has served as a General Co-Chair of COMSWARE 2008, a Program Committee Co-Chair of ACM Multimedia 2007, IEEE WoWMoM 2007 and COMSWARE 2007, and a Co-Chair of IEEE GLOBECOM 2011 Wireless Networking Symposium. He has also served on Program and Organization Committees of numerous leading wireless and networking conferences including ACM MobiCom, IEEE INFOCOM, IEEE SECON, and IEEE WoWMoM. He is also currently serving as an Editor of IEEE Transactions on Wireless Communications, and served as an Editor of IEEE Transactions on Mobile Computing, IEEE Wireless Communications Magazine, ACM SIGMOBILE Mobile Computing and Communications Review, Journal of Communications and Networks, Computer Networks, and Computer Communications. He has served as a Guest Editor for IEEE Journal on Selected Areas in Communications, IEEE Wireless Communications, and ACM Wireless Networks. From 2000 to 2007, he was an active contributor to IEEE 802.11 WLAN Working Group. He has received numerous awards including KICS Dr. Irwin Jacobs Award (2013), Shinyang Scholarship Award (2011), Presidential Young Scientist Award (2008), IEEK/IEEE Joint Award for Young IT Engineer (2007), Outstanding Research Award (2008) and Best Teaching Award (2006), both from the College of Engineering, Seoul National University; the Best Paper Award from IEEE WoWMoM 2008, and Recognition of Service Award (2005, 2007) from ACM. Dr. Choi was a recipient of the Korea Foundation for Advanced Studies (KFAS) Scholarship and the Korean Government Overseas Scholarship during 1997-1999 and 1994-1997, respectively. He was named IEEE Fellow in 2014 for the contribution to the development of WLAN protocols.

Kwang Bok Lee received the B.A.Sc and M.Eng. degrees from the University of Toronto, Toronto, ON, Canada, in 1982 and 1986, respectively, and the Ph.D. degree from McMaster University, Canada, in 1990. He was with Motorola, Canada, from 1982 to 1985, and Motorola from 1990 to 1996 as a Senior Staff Engineer. He joined the Department of Electrical and Computer Engineering, Seoul National University, Seoul, Korea. Currently, he is a Professor in the Department of Electrical and Computer Engineering. He was the Head of the Department of Electrical and Computer Engineering, from 2011 to 2015, and the Director of the Institute of New Media and Communications, from 2007 to 2009. He has been serving as a consultant to a number of wireless industries. His research interests include mobile communications and communication technique covering physical layer and upper layer. He holds 29 US patents and 37 Korean patents, and has a number of patents pending. He was an editor of the IEEE Transactions on Wireless Communications, from 2002 to 2012. He has been an auditor of KICS since 2015, and was the Vice President of publication and member relations of KICS, in 2014. He was a co-chair of the International Conference on Communications (ICC 2005) Wireless Communication Symposium, and was a chair of the IEEE Communications Society Seoul Section from 2005 to 2010. He received the Best Paper Award from CDMA International Conference 2000 (CIC 2000), and the Best Teacher Award in 2003 and 2006, respectively, from the College of Engineering, Seoul National University. He received the Special Award from the Samsung Advanced Institute of Technology in 2005 and received a Korea Engineering Award from the Korea Science and Engineering Foundation and Ministry of Education and Science Technology in 2010. He is a Fellow of the IEEE.